Intelligent Agents Supporting Digital Factories

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***Abstract*—Intelligent agents represent a widely exploited paradigm of the Distributed Artificial Intelligence (DAI). They have been applied in many fields, and recently they have appeared also in the digital factory field. Digital factories are abstractions of real factories, which enable high-level management of factories' processes, along with their automatization. So, the real factories can dynamically adapt their processes to unexpected situations.**

In this paper, we survey different works at the state of the art that show how intelligent agents can support digital factories, along with the limitations of their application. A discussion about the advantages of intelligent agents and the open issues completes the paper.

***Index Terms*—Intelligent Agents, Digital Factory, Industrial IoT.**

I. Introduction

Digital factories [1] represent a key enabling paradigm for the next generation of smart manufacturing. Digital technologies promote the integration of traditional product design processes, manufacturing processes, and general collaborative business processes in order to bridge the gap between design and manufacturing processes of a traditional factory [2]. To this end, the digital factory covers the entire product lifecycle ranging from the product design stage down to product planning and realization. The new wave of technologies that could lead to the fourth industrial revolution, the so-called *Industry 4.0*, is further multiplying the opportunities to get access to global supply and sale markets.

Intelligent agents [3] are decentralized software components that exhibit some main features, such as *autonomy*, *reactivity*, *proactivity* and *sociality*, which can be enhanced with other ones such as *mobility* and *learning ability*; all these features lead them to be "*intelligent*" in a Distributed Artificial Intelligence (DAI) fashion [4]. Thanks to these features, a proper implementation adds flexibility to software systems and applications thus leveraging the development of autonomous systems [5], [6].

In this paper, we propose a survey of agent-based approaches in the digital factory field. Thanks to the previously mentioned features, intelligent agents have been considered in the development of digital abstractions aiming at providing a means to manage real factories and all the required interactions in a flexible way.

Some surveys have already been proposed [7], [8], [9] in the field; we report about their results, but we point out that our work is more *specific* on the one hand, because we focus on the agent methodologies for the realization of digital factory tasks, and more *general* on the other hand, because we consider digital factories as a key paradigm embracing multiple aspects related to the digitialization of factories.

The rest of this paper is organized as follows. Section II presents the existing approaches that exploit intelligent agents in digital factories, starting from some existing surveys related to those topics (Section II-A). Section III discusses the presented approaches and reports the advantages and limitations of adopting agent-based technologies in digital factories. Finally, Section IV concludes the paper and sketches future directions.

II. Intelligent Agents for Digital Factories

This section is devoted to present the work related to intelligent agents applied to the field of in digital factories. Some surveys already exist and we summarize them for completeness's sake (Subsection II-A). Then, we present the existing approaches, divided into three subsections:

- Agent-based decentralized management
- Agent-based data management
- Agent-based architectures

Of course, not all reported works fit perfectly in a category, but we think that this can be useful to have an idea about the topics addressed by the existing works.

A. Surveys in the Literature

In the literature we can find some surveys of the researches related to the application of the AI technologies to the manufacturing field. we think that they can be useful to readers interested in the topic; nevertheless, the rest of the paper will focus on *intelligent agents* (which can be conceived as a specific AI technology) and *digital factories* (which can be seen as an implementation of intelligent manufacturing).

[7] presents a survey focusing on Multi-Agent Systems (MASs). As application field, it is limited to the manufacturing *production*, while our survey concern digital factories in general, which involve also other manufacturign aspects. The paper proposes a classification of the MAS into two main categories: *centralized* multi-agent coordination and *decentralized* multi-agent coordination. The former exploits a *coordinator* agent that manages all other agents and comprises a *facilitator* agent, which coordinate the communication between agents, and a *mediator* agent, which takes decisions on low-level aspects. In the latter category, agents have a high degree of autonomy, and thus the control is spread over all agents. The paper highlights the advantages of exploiting agents in manufacturing systems,

mainly in terms of coordination of manufacturing components.

[8] presents a survey of technologies for Industry 4.0 classifying previous works into five categories:

- Concept and perspectives of Industry 4.0
- CPS-based Industry 4.0
- Interoperability of Industry 4.0
- Key technologies of Industry 4.0
- Applications of Industry 4.0

The intelligent agents represent a future direction of Cyber-Physical Systems (CPS) and also as a key technology at the base of several aspects such as products, orders, machine processes, controls; in addition, agents can provide interoperability among the participants in the manufacturing product chain.

[9] discusses the use of agent-based methodologies in projects in the field of Cyber-Physical Production Systems (CPPS), which can be considered part of digital factories. Two aspects are identified in order to classify the existing projects. The former is the CPPS type, which can be one or more of the following:

- Demonstrators
- Smart manufacturing approaches
- Electric Grid applications
- Architectures

The latter aspect considered is the ISA 95 levels [10], which can be:

- Device Level (L1)
- Supervisory Control And Data Acquisition or SCADA Level (L2)
- Manufacturing Operations Management or MOM Level (L3)
- Enterprise or ERP Level (L4)

In addition, the authors define requirements for agent-based methodologies in order to be suitable for the development of CPPS, as follows:

- Minimal conditions
- Intelligent characteristics attributes
- Formalized modeling terms
- Systems and human integration needs

Starting from the above aspects, the authors classify the existing agent-based methodologies concluding that they have several attributes to meet the CPPS requirements, but some specific requirements still need attention from the developers; in particular, they mention *vertical integration*, *human integration*, *proactivity* and *abstraction*. The lack of proactivity and abstraction is surprising, because they are two of the main features of agents [3]. The other two features are instead expected and are worth being subject of future researches.

B. Agent-based Decentralized Management

1) Knowledge and agent-based system for decentralized scheduling in manufacturing: In [11], authors propose an innovative group of algorithms for agent systems allowing them to sequence their plans of operation and to adjust the timing of those manufacturing operations cooperatively. A frequent issue in manufacturing contexts consists, in fact, of jobs with rigid plans. Established approaches usually perform conflict resolution in a way that forces involved agents to wait until they are allowed to sequence and time the next operation.

The assumption behind those approaches is removed in [11], thus allowing operations to be scheduled in parallel. More specifically, the authors discuss an innovative mechanism enabling the emergence of manufacturer operation schedules from a generic collection of decentralized algorithms. This mechanism allows agents to independently sequence their operations with regard to their constraints while enabling cooperation.

As case studies for assessing the proposal, the MT6, MT10, and LA19 job scheduling problems were used. Furthermore, an industrial use case was detailed to provide context to the manufacturing environment under investigation. It has been shown that agents could generate plans of operations by executing in parallel thus reducing the computation and communications efforts 10X and 5X respectively. It has also been found that the proposed family of algorithms are capable of addressing disturbances such as delays and last rush jobs.

2) Decentralized and on-the-fly agent-based service reconfiguration in manufacturing systems: The work reported in [12] deals with the problem of service manufacturing reconfiguration in industrial manufacturing systems. In this work, the authors examined the service reconfiguration problem in a real-time constrained environment. In particular, concerning the physical equipment of the factory which reconfiguration is only possible when it satisfy timing requirements. To this end, the author proposes a system for identifying dynamic reconfiguration opportunities as well as the selection of the best reconfiguration strategies to optimize productivity. The proposed MAS consist of three-type of agents: Resource Agent (RA) which encapsulate the physical operation of a machine as a service. Product Agent (PA) represents a service consumer and fulfill the production demand by creating new products. PA and RA have different services reconfiguration needs. RA covers the changes of structure of a composed service while PA focuses on changing the services catalog as well as modification of their behavior. The MAS is enriched with early detection of reconfiguration opportunities. To this end, the detection of a reconfiguring phase is performed through continuously collecting data and analyzing them to trigger a reconfiguration opportunity (i.e., changing in a service, degradation of service performances, trend or pattern in a service performance). When an event is triggered, a set comprising possible service reconfiguration strategies is computed by each agent. To reduce the space of strategies generated by a single agent, a matching mechanism is proposed to analyze the performance of a strategy in a given context. The feasibility of a reconfiguration strategy is evaluated using the JENA framework which exploits semantic reasoning about the logic of a solution to assess its applicability. In the end, an optimal reconfiguration strategy is selected by ranking feasible solutions using a multi-criteria function which quantifies the benefit of adopting a strategy on the other. For a collaborative environment comprised of multi-agents, an interaction protocol is proposed to ensure that a selected strategy is optimal for the whole system. The proposed service reconfiguration approach is evaluated on a real-case scenario of a manufacturing system comprised of five workstations connected by a conveyor system. The results reported by the authors demonstrate the benefit of a service reconfiguration mechanism with an increasing of the productivity. Moreover, the proposed interaction protocol shows the advantage of distributing the service reconfiguration problem as the number of generated candidate strategies increase.

3) Potential of a Multi-Agent System Approach for Production Control in Smart Factories: The paper [13] presents a multi-agent framework for control, planning and scheduling production autonomously and adaptively. The model is built from real data of a production line of an automotive and then it is simulated to evaluate the performance. Six types of agents are defined to control the production, and in particular, the supervisor agent communicates real-time information about the status of the product agents and machine agents. Based on the received messages, the coordinator agent selects the machine that will perform the next job adopting a two-step decision rule. The decision rule takes into consideration the type of the task as well as the availability of a machine to carry out the job. MAS performances are evaluated on four scenarios in which the model is compared with the traditional scheduler. An enhancement common to all the experiments is represented by the flexibility introduced by the MAS.

Thanks to the capability of assigning a priority value to the production of a batch and the ability to enqueue products for delayed manufacturing, the production becomes more flexible compared to the traditional scheduling system. Additional experiments are further described in order to evaluate the capabilities of the MAS to react to machines failures. The real-time communication between the coordinator agent and the supervisor agent allows the system to be aware of machine failures and react by assigning the task to the first non-faulty machine. Finally, from a performance evaluation perspective, the MAS simulation help to focus not only on the scheduling efficiency but in general to the overall system performances in particular cases where machines are added or removed from the shop floor.

C. Agent-based Data Management

1) A self-organized multi-agent system with big database feedback and coordination: Authors of [14] propose a conceptual smart factory framework based on a multi-agent system. The manufacturing shop floor is composed of four different categories of autonomous agents, which share common knowledge and communicate with each other to reach a system-wide goal. In order to overcome limited decision capabilities of agents caused by poor knowledge of the environment in which they act, a Contract Net Protocol mechanism is proposed to enhance cooperation and collaboration among the distributed entities. The negotiation takes place between an agent, elected as a manager, and the other agents (named contractors). The agent manager is capable of initiating new rounds and taking decisions based on the received messages sent by the agent contractors.

A typical negotiation involves the following steps: 1) A manager initiates a new task. 2) Each contractor either send a bid message to take part in a new round or a busy message. Depending on received messages, the manager ranks bidders according to a predefined set of layered rules. As an example, the task of finding a conveying path requires to determine the next available hop of the route. In this scenario, the agent manager will select the highest-ranked bidder as the winner of the negotiation, and it becomes the next hop of the path. Conditions of deadlock between multi-function and multi-occurrence agents are further examined, and a solution based on congestion control is presented. In contrast to other strategies (i.e., functional redundancy and replication of agents) which cannot guarantee deadlock prevention, the proposed mechanism effectively prevent deadlock even if less efficient compared to the other approaches.

2) Data-driven decision making for supply chain networks with agent-based computational experiment: One of the key issues in supply chain networks is decision making for solving operational problems. Authors of [15] recognizing the importance of business analytics based on multi-dimensional data and decision support systems, propose a data-driven methodology for decision support in supply chain networks. A four-dimensional-flow model is proposed to satisfy data requirements of decision-making. In this work, agents are employed in a computational experiment to generates a comprehensive operational dataset of a supply chain thus verify the solution produced in the decision making. In particular, a data-driven decision-making framework for supply chain networks is proposed, and two solutions based on business analytics are put forward. The framework is evaluated on a real-case scenario of a five-echelon manufacturing supply chain network. In particular, results demonstrated the effectiveness of the proposed four-dimensional-flow model in representing operations typical of supply chain networks. The agent-based computational experiment allowed to generate a comprehensive dataset but also to verify solution of decision making. The data-driven methodology presented offers a valuable tool for the decision-making process into the supply chain domain.

3) Intelligent sustainable supplier selection using multi-agent technology: Theory and application for Industry 4.0 supply chains: Ghadimi et al. [16] analyze the problem of suppliers evaluation and selection for the management of supply chains (Scs) within the context of Industry 4.0. Although the problem has been addressed before, sustainable supplier selection needs are further investigated to enhance green and lean Scs concepts into Industry 4.0. To this end, the authors propose a MAS for sustainable supplier selection. The process of supplier evaluation conducted in their work is divided into four steps as follows: i) Identification of components and products to be supplied. ii) Definition of impact factors of sustainability typically defined by manufacturer requirements and then utilized during the supplier evaluation phase. iii) Suppliers assessment is conducted via data gathered on the basis of manufacturer requirements. iv) Suppliers evaluation is based on a score which permits to evaluate their capabilities in terms of sustainability.

The evaluation process is modeled as a MAS in which negotiation takes place between a buyer (manufacturer) who collaborate with multiple sellers (suppliers). The proposed architecture of the MAS is composed of three-layer named as interface layer, technical layer, and data resource layer. The interface layer allows both manufacturers and suppliers to update information utilized during the evaluation process. The resource layer is comprised of the data management systems which store both information provided by the manufacturers and suppliers as well as the evaluation performance score of each supplier. The technical layer mediates between other layers to retrieve data for the evaluation process of the suppliers. The MAS developed by using the JADE framework consists of one container which will be ideally hosted by a manufacturing company while other containers will be maintained by suppliers connected to the main container. Agents of different containers interact using a FIPA protocol to fulfill the evaluation process following a predefined schema. Authors also introduce the designed evaluation model used by the decision-maker agent in order to periodically evaluate the geographically dispersed suppliers. A FIS model is proposed to deal with uncertainty and lack of magnitude of sustainability information. The evaluation of the data is based on fuzzy set theory. To evaluate the sustainability of the MAS an implementation of a real-case scenario regarding the medical sector is proposed. The scenario consists of one manufacturer providing electronic medical devices and nine suppliers producing different components. Results had shown an improvement in terms of economic sustainability increase the performance evaluation score of suppliers. Therefore, this information is propagated to the right supply chain member in time. In conclusion, the developed MAS promote to enhance sustainability among supply chain networks in the context of industry 4.0 by enabling interconnection among Scs, Real-time information, decentralization, and reduced human interaction.

D. Agent-based Architectures

1) CASOA: An Architecture for Agent-Based Manufacturing System in the Context of Industry 4.0: In [17], authors present a self-organizing architecture making use of agents communicating and negotiating through a cloud network. Knowledge is organized into representations based on ontologies for providing the basis for decision-making. Thus, agents can reconfigure their network in a prompt and collaborative way. Because the interactions among agents in distributed systems are often difficult to be understood and predicted, their interaction behaviour has been modeled as a hierarchical structure.

The architecture has been assembled around agents of four types: suggestion, product, machining, and conveying agents. Each and every type of agent is focused on different manufacturing-related functions. Agents use the most proper methods for communicating their internal reasoning data. Furthermore, a mechanism based on the cloud network has been introduced for coordinating the agents. For eliminating eventual local optima in the case of distributed scheduling, the cloud-assisted layer collects data from the lower layer and defines the optimal scheduling policy through data analysis. These policies are fed back to the plants for assisted scheduling in form of suggestions.

Experimental results have shown that this architecture can be deployed to build smart manufacturing system with limited efforts and can improve the capabilities of adaptation and robustness of manufacturing system when dealing with multi-product problems. Finally, the results showed that the dynamic scheduling policy proposed has clear advantages over more traditional and static scheduling policies. In particular, CASOA showed remarkable robustness and capacity of adaption to frequent product changes and inferences to the production process.

2) An agent-based monitoring architecture for plug and produce based manufacturing systems: The article [18] proposes a MAS architecture to support the monitoring of a shop floor in the case of dynamic entities join or leave the system thus changing the network topology. The proposed architecture is based on three different agents. A low-level agent is responsible for abstracting a physical resource (CNC, machine, robot). At a higher level, the monitoring agent abstracts low-level components to represent a high-level subsystem. This agent receives data from both devices positioned on the field and lowest-layer agents. Finally, a coordinator agent is responsible for monitoring the system behavior in terms of subsystems as well as single components. A knowledge base containing a set of predefined rules allows each agent to determine useful events to be aware of. Inter-layer communication is based on CNP (Contract net Protocol) and the Foundation for Intelligent Physical Agents (FIPA) request protocol. The CNP protocol is used to perform task negotiation, while the FIPA protocol is adopted to establish point-to-point communication between agents. This architecture presents a benefit in terms of enhanced monitoring performances thanks to a decentralized analysis of the raw data. External components such as remote servers are involved in incrementing the computational capabilities and therefore processing a massive amount of data. The system results in better and accurate monitoring.

3) Agent-based fault tolerant framework for manufacturing process automation: Agent-based approaches are often used for dealing with manufacturing-related disruptions regarding machine faults. disruption of manufacturing processes, in fact, adversely affect productivity and efficiency while down times affect the whole chain of value.

Widely used solutions to these issues are centralized and mostly focused on the detection and isolation of a particular disruption. Unfortunately, this kind of centralized approaches suffers of time lags between the moment in which data are analyzed and a response is generated.

[19] proposes an alternative approach for mitigating disruptions by deploying a fault tolerant framework based on agent technologies. The technique is adopted for handling fault detection and identification and for further investing the root cause of the disruption. Once a disruption is identified, a weight is assigned to it, and the eventual corrective mechanism is executed.

This agent-based model has been tested on an asphalt manufacturing plant. Results showed a reduction in downtime around 5%. Additionally, 37% reduction in the number of failures has been noticed. This can lead to an increase of about 5% in the overall productive activity. As a consequence, this method offers a promising opportunity for enhancing the overall efficiency of manufacturing plants when compared to more traditional approaches.

III. Summary

The literature presents a small number of approaches in which intelligent agents are applied to digital factories. The concept of digital factory can be found in different shapes, among which *Smart manufacturing*, *Industry 4.0*, *Cyber-Physical Production Systems*, *Smart factories*; we consider them as sorts of "implementations" of the more general concept of digital factory, but still very interesting also because they can propose different points of view.

The survey of the approaches we have proposed highlights the *advantages* of applying intelligent agents in digital factories; the main ones turn out to be:

- *Autonomy*. Agents can manage the real factory reducing the need for human intervention.
- *Adaptation*. Agents can rely on different plans in order to flexibly adapt to different situations.
- *Decentralization*. Agents allow for scalable decentralized solutions with neither bottlenecks nor single points of failure.
- *Robustness*. Agents can react to an unpredicted situation in a flexible way and grant reduction in the process downtime.

From our survey emerges that there are also some *limitations*; in particular, agent-based approaches can be further improved in the following directions:

- *Simplicity*. The autonomy of the agents leads to complex interactions that could be difficult to define and manage; this calls for a simpler means to enable the management of interactions, possible customized to the digital factories field. This can increase the acceptance of intelligent agents in digital factories.
- *Human integration*. Despite the decreasing of human intervention, what emerges is that humans' contribution is still an important part of real factories, and their involvement in the system (usually called "human in the loop") cannot be avoided in digital factories.
- *Real-Time*. Several tasks in real factories are likely to have real-time constraints that influence the overall productivity; they cannot be disregarded by the digital counterpart, and from this point of view intelligent agents may be inadequate to tackle them. This aspect must be further investigated and deserves appropriate solutions.

IV. Conclusions and Future Work

In this paper, we analyzed the current trends in the implementation of agent-based digital factories. As shown by the mentioned works, the adoption agent-based architectures optimize many of the tasks of traditional factories by exploting agent characteristics. Although, the effectiveness of agents promotes a concrete support for the digitalization of traditional manufacturing tasks, the number of implementations in the industry is not significant; we think that this is due to the limitations analyzed in the paper and briefly sketched in three key points as follows:

1) Simplicity of agent interactions is required to have systems easier to design and more controllable. This prerequisite is fundamental in order to keep as simple as possible the management of complex manufacturing tasks and their integration.
2) The *involvement of humans* [20] is an important aspect when real factories are managed through digital abstractions, thus human plays an active roles and therefore must be considered as part of the digital processes.
3) *Real-Time* constraint in a MAS, need to be further examined in order to fulfill timing requirements of tasks and services of IoT based digital factories. The enablement of a digital twin models in a digital factory requires real-time data exchange among the virtual and the real factory. In this scenario, legacy manufacturing systems must be integrated with high end manufacturing equipments IoT devices, robotic arms, and robots to enable a flexible and transparent real-time communication.

On the other side, the advantages of the application of agents in a digital factory are mainly related to *autonomy*, *adaptation*, *decentralization*, and *robustness*. These advantages enable the applicability of the agent paradigm to the digital factory field in order to fulfill various manufacturing tasks related to digital factory lifecycle. With regard to future work, we point out interoperability issues intra- and inter-factories since it is a key issue that not only leverage the adoption of digital factories and its effectiveness [21], but also promotes the enablement of new form of collaborations between enterprises. The interoperability challenges between digital factories can be tackled through the adoption of agent-based systems.

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